

## A Fluoropolymer Blend with High Ionic Conductivity

### Field of the Invention:

The object of the invention is to provide a fluoropolymer blend with high ionic conductivity, more particularly, which is applicable to an electroactive polymer composite (EAPC) membrane housing excellent thermal resistance, acid-alkali resistance, mechanical strength, curvature, and flexibility.

### Background of the Invention:

Common 3C video photoelectric products (computer, communication, and consumer electronics) are expected to continue to become the star industry for Taiwan after she entering the 21<sup>st</sup> century. The market requirement shows that the product specifications for monitors, laptop computers, desktop computers, cellular phones, and other data storage device have already developed lightness, thinness, shortness, smallness, and multifunction capabilities. These trends are expected to be widened to all the 3C video products. For thin plastic pieces, especially for the outer shell, the requirement for the characteristics of resistance to sound, vibration, heat, and electromagnetic waves has become a necessity. Nowadays, because of the limitation of materials, actuators of optical, thermal, and electric mechanisms cannot fulfill the requirement of the next generation for extra-lightness, -thinness, -shortness, -smallness, and low energy consumption. EAPC has the merits of lightness, elasticity, low power consumption, long life cycle, and quick reaction, and is the optimal choice for a brand new actuator. The actuators, manufactured by this material include: micro pumps, optical switches, grippers, fans, optical-valves, lens controllers, focus lenses, micro-mirrors, and active noise controllers, and may be applied in the products of machines, micro devices, 3C component assemblies, photoelectric devices and other artificial muscle for medical treatment. In tradition, the most typical ionic polymer for EAPC intelligent composite is Nafion. A membrane made by this material has narrow ionic passages, by which water or ion is transferred quickly. However, the passages are easily destroyed to interrupt the transfer due to the dehydration of the material. Also, the price of the material is

extremely high, it is not easy to handle, and the manufacture of this material is very complicated.

In order to further apply this kind of material in increasingly precise and miniature electronic products, research of this field has shown that there are still many shortcomings:

US Patent No. 4,308,359 discloses a limited application of PVDF-g-SPS (styrene-grafted and sulfonated PVDF).

In a compound method of PVDF-g-SPS mentioned in the literature of *Electrochem Acta*, 43, NoS, 12-13, p1881~p1890, a PDVF membrane is irradiated under 175KV, 100kGy, then immersed in styrene solution to form a grafted product which is sulfonated to form PVDF-g-SPS. This product may be applied in a conduction membrane of a hydrogen ion or fuel cell, but it is still necessary to enhance its effect.

In the literature of *Materials Research Society Symposium Proceeding Vol. 600*, P267, 2000, Materials Research Society, a test piece made by polyvinyl acetate applies Au as an electrode, but it still has the shortcoming of easy breakage.

In the literature of *Materials Research Society Symposium Proceeding Vol. 600*, P229, 2000, Materials Research Society, a macromolecule electrolyte membrane of Nafion or Flemion with a perfluorinated structure applies Au as an electrode. The membrane may be deflected under the driving of low voltage, but its application field is very narrow, and it is not easy to change properties and mass production.

In US Patent No. 5,403,675, a macromolecular with the rigid-rod of polyphenyl is sulphonated to make PEM to replace Nafion for reducing the price and maintaining excellent conductivity. But, the shortcomings of such kind of molecule are its solubility to water is too large during high ionization; the conductivity is worsened during low ionization; and the stability is poor.

In US Patent No. 5,795,496, a sulphonated PEEK replaces the Nafion and is made as dense surface membrane for reducing the penetration rate of methanol, and is applied in a fuel cell. Its shortcomings are that the solubility to water is great

for the S-PEEK and the conductivity of the membrane is lowered when the ionization of the dense surface membrane is reduced.

From above description, there is a need to develop a conductive membrane that has excellent characteristics and competition to drive macromolecular composite electrically for reaching the requirements of high mechanical strength, high conductivity and high stability.

### **Summary of the Invention**

The object of the invention is to provide a fluoropolymer blend with high ionic conductivity that may be applied in an electroactive polymer composite (EAPC). The membrane has the characteristics of excellent thermal-resistance, acid-alkali resistance, mechanical strength, curvature, and flexibility, etc., and also has the tensile strength over 250kg/cm<sup>2</sup>.

Another object of the invention is to provide a fluoropolymer blend with high ionic conductivity that may be applied in an electroactive polymer composite (EAPC) membrane. The membrane has excellent mechanical performance and may also be cross-linked under the alkaline circumstance of diame or peroxide for further enhancing its mechanical performance.

Further object of the invention is to provide a fluoropolymer blend with high ionic conductivity that is comprised of PVDF-g-SPS (styrene-grafted and sulfonated PVDF), PVDF (poly [vinylidene fluoride]), and fluoro- or hydrocarbon-elastomer. The compound membrane may obtain appropriate mechanical performance and flexibility by proportional adjustment of above components.

In order to achieve above objects, the invention particularly provides a fluoropolymer blend with high ionic conductivity that may be applied in an electroactive polymer composite (EAPC) and includes following components: PVDF-g-SPS, PVDF, and hydrocarbon- or fluoro-elastomer. The invention is a blend assembled by these three components, that is, PVDF-g-SPS, hydrocarbon- or fluoro-elastomer, and PVDF. After mixing the PVDF-g-PS, hydrocarbon- or fluoro-elastomer, and PVDF with specific proportion and dissolving them in an oily or non-oily solvent of non-proton or proton of high boiling point, the solution is coated on a

substrate and is heated to get rid of the solvent afterwards to get a compound membrane. Then, a compound membrane of PVDF-g-SPS may be obtained by sulphonating the aforementioned compound membrane. The obtained compound membrane has excellent properties, such as thermal stability, acid-alkali resistance, good mechanical performance, excellent flexibility, and capability for processing appropriate cross-link for further enhancing the mechanical performance of this membrane.

In addition, there is another characteristic for the compound membrane of PVDF-g-SPS according to the invention. That is, the degree of grafting (defined as:  $d.o.g. = [m_1 - m_0] \times 100\%$ , where  $m_0$  is the mass of PVDF, and  $m_1$  is the mass of grafted PVDF) of the PVDF-g-PS in the process may be adjusted at random, and after it being sulfonated, different ionic group content of PVDF-g-SPS may be obtained. The properties of chemical resistance and mechanical performance of the PVDF-g-SPS of high ionization rate can also be enhanced because of adding the hydrocarbon- or fluoro-elastomer, while the increase of adding proportion of hydrocarbon- or fluoro-elastomer may also raise the flexibility of the compound membrane appropriately. Therefore, the compound membrane of PVDF-g-SPS according to the invention may fulfill the functions that can not be obtained by prior arts, that is, its mechanical strength or flexibility can be raised according to the necessity, or both can be fulfilled as requirement at the same time.

### **Detailed Description of the Preferred Embodiment**

The process of the compound membrane blend of fluoropolymer with high ionic conductivity is to contain the sulfonic acid group as the main component for the PVDF-g-SPS. First, the process flow path of the PVDF is to graft the styrene monomer onto the PVDF to become the PVDF-g-PS by the applications of x-ray, electron beam,  $\gamma$ -ray or plasma method. However, appropriate degree of grafting (defined as:  $d.o.g. = [m_1 - m_0] \times 100\%$ , where  $m_0$  is the mass of PVDF, and  $m_1$  is the mass of grafted PVDF) may make the resin maintain its original mechanical performance and keep appropriate solubility in solution to facilitate following reaction or working procedures. In order to reach the appropriate degree of grafting, we may control the amount of monomer usage, kind of irradiator, and time of irradiation to change the degree of grafting rate as required. Then, the PVDF-g-SPS can be obtained by sulphonating the PVDF-g-PS with sulfphonating reagents, such as strong sulfuric acid, chlorosulfonic acid or burning sulfuric acid.

As a general rule, several factors may influence the properties of the resin:

(a) During low degree of grafting, although the mechanical property of the thin membrane made by solvent method is better, the containment of sulfonic acid group is low and water uptake ratio (defined as  $[m_s - m_d / m_d] \times 100\%$ , where  $m_s$  is the mass of swelling membrane, and  $m_d$  is the mass of dry membrane) is also low, so its ionic conductivity is worse.

(b) When the degree of grafting of the styrene is higher than 45%, the containment of sulfonic acid group is increased to make better ionic conductivity. But, the membrane formation is worse, neither is the mechanical property to cause the thin membrane easy to break, so its application is limited greatly.

(c) The membrane made by the PVDF-g-SPS only is difficult to apply in an electroactive polymer (EAP) material. Although its ionic conductivity and mechanical strength may reach the requirement, its hardness is too great to get a good flexibility, so even swollen by water, the membrane still cannot be driven by external electric voltage due to too great rigidity.

The above-mentioned shortcomings can all be improved by the technique disclosed by the present invention, which is a blend assembled by three

components, that is, PVDF-g-PS, hydrocarbon- or fluoro-elastomer, and PVDF. After mixing the PVDF-g-SPS, hydrocarbon- or fluoro-elastomer, and PVDF with specific proportion and dissolving them in an oily non-proton solvent with high boiling point, the obtained solution is then coated on a substrate and is heated to get rid of the solvent to get a compound membrane. A desired compound membrane of PVDF-g-SPS can be obtained by sulfonating the compound membrane by aforementioned sulfonating method. The obtained compound membrane of PVDF-g-SPS has following properties:

(a) Excellent thermal stability: this compound material of thin membrane is extremely stable in the atmosphere below 200°C and only starts to decompose gradually above 250°C, and the 50% decomposing temperature according to TGA is 345°C.

(b) Acid-alkali resistance: this compound material of this membrane is still not decomposed even if stored for a long time in a solution with PH range of 1 to 14.

(c) Excellent mechanical performance: its tensile strength may exceed 250kg/cm<sup>2</sup>.

(d) Excellent flexibility.

(e) The mechanical performance and thermal resistance of this membrane may also be further enhanced by an appropriate cross-linking process under the existence of alkaline compound by using diame or peroxide.

Besides above-mentioned advantages, another characteristic of the compound membrane of PVDF-g-SPS according to the invention is that the degree of grafting of the PVDF-g-PS can be adjusted at random, and after it is sulfonated, different ionic group content of PVDF-g-SPS may be obtained. The properties of chemical resistance and mechanical performance of the PVDF-g-SPS of high ionic group content can also be enhanced because of adding the hydrocarbon- or fluoro-elastomer, while the increase of adding proportion of hydrocarbon- or fluoro-elastomer may also raise the flexibility of the compound membrane appropriately. Therefore, the compound membrane of PVDF-g-SPS according to the invention may fulfill the functions that cannot be obtained by the prior art, that is, its mechanical strength or flexibility can be raised as necessary, or both can be fulfilled at the same



time.

The number average molecular weight ( $M_n$ ) of the PVDF resin powder applied in manufacturing the PVDF-g-PS according to the invention is preferably between 80,000 and 350,000 and the best one is between 120,000 and 230,000. The resin of such molecular weight has excellent mechanical performance also has good properties of chemical resistance, and thermal resistance. The graft reaction of styrene monomer is proceeded by the irradiation of  $\gamma$ -ray, electron beam, x-ray or plasma method. Its degree of grafting is preferably between 10% to 100%, but preferably between 30% and 65%. The control of this degree of grafting may be determined by the dosage of radiative irradiation, irradiation time, and the concentration of the monomer. The appropriate graft following the procedure of ionization may introduce the desired sulfonic acid group that is served as the main source of water absorption for the membrane, also is provided as the main passage of transfer inside the membrane for the ions and water. The resin powder may be ionized directly after being grafted, or ionized after the formation of a membrane by the solvent method. In general ionization method, it applies strong sulfuric acid, burning sulfuric acid, or chlorosulfonic acid, while the reaction time is determined by the particle diameter, membrane thickness, acid reagent concentration, reaction temperature, and sulphonation rate, etc. As a general rule, the reaction can be completed within three hours at room temperature. The degree of sulfonation may be determined by analyzing its containment of  $-\text{SO}_3\text{H}$  group by the acid-alkali titration method, the degree of sulfonation being the percentage of sulfonated phenyl group (ratio of sulfonated phenyl groups to total phenyl groups).

The hydrocarbon-elastomer described in the invention may be acrylic-elastomer, while the fluoro-elastomer may be Viton (copolymer of vinylidene fluoride/hexafluoropropylene from 3M Co.), the terpolymers of vinylidene fluoride/hexafluoropropylene/tetrafluoroethylene, or the mixture of above-mentioned hydrocarbon- and fluoro-elastomer or different fluoro-elastomers. Wherein, the acrylic-elastomer may be the poly ethyl acrylate or the derivatives of other alkyl, and its number average molecular weight is preferably between 100,000 and 300,000, and the best one is between 150,000 and 250,000. The number

average molecular weight of the fluoro-elastomer is preferably between 80,000 and 2,800,000, and the best one is between 100,000 and 200,000. The adding amount of above elastomers is 10~60% of the weight of the entire blend.

The solvent applied in dissolving above-mentioned PVDF, fluoro- or hydrocarbon-elastomer, and PVDF-g-PS is an aprotic with high boiling point, such as: dimethylformamide, 1-methyl-2-pyrrolidone, dimethyl sulfoxide or the mixture thereof. In addition, small amount of protic solvent may be added in these solvents, and the preferable temperature for manufacturing the membrane with these solvents is between 20°C and 200°C, and the best one is between 60°C and 120°C. Besides the solvent method, any other well-known method for manufacturing the membrane may also be applied, such as: thermal press method, rolling-and-winding film method, or extruding method, etc.

Other interface activators may be added as assembling components for above-mentioned membrane, such as: the fluoro-surfactants of FC-430, FC-431, Fc-135, etc. of the 3M company, or the hydrocarbon surfactants of Allyl alcohol-1, 2-butoxylate-block-ethoxylate, etc. of the Aldrich company. These surfactants may facilitate the sufficient and uniform combination among each polymer component to smoothen the membrane easily and are helpful to promote the properties of the membrane.

The materials of the invention have been developed through the molecular simulation and computational analysis by computer for researching the relationships among ionic group content, hydration, movement, and the molecular chemical structure, etc. These researches are beneficial to the molecular structure design for new fluoro-series ionic polymer or other characteristics. Further computational analyses may evaluate the feasibility and properties of the composition of key monomers and/or ionomer with different chemical structure.

To implement the content of the invention in more practical way, several preferable embodiments are presented as following for describing the content of the invention in more detail.



### First Embodiment

First, the process for manufacturing the PVDF-g-SPS membrane: add a styrene monomer weighted 20~40 grams of 99.9% purity into the PVDF resin powder (average particle diameter is 0.25~0.40 $\mu$ m and Mn = 200,000) weighted 30~70 grams, after being agitated, the mixture is irradiated with the intensity of 10~35kGy for proceeding the graft reaction. After being filtered, the graft copolymer thus obtained is extracted with acetic acid ethyl ester in Soxhlet apparatus for 8 hours. The obtained solid product is white particle and weighted 60~100 grams, and its degree of grafting is 30~50%. Further, the PVDF-g-PS product has no decomposition phenomenon (TGA, 10°C/min) below 400°C. Furthermore, with the 1-methyl-2-pyrrolidone as solvent, add dry PVDF-g-PS weighted 2~5 grams, poly ethyl acrylate (Mn value is 190,000) weighted 4~8 grams, interface activator FC-431 weighted 0.1~0.5g, and PVDF (Mn value is 200,000) weighted 5~9 grams into the 1-methyl-2-pyrrolidone solvent of 100~300ml. These mixture is agitated continuously under the temperature of 60~90°C until all the components are dissolved. The solution is coated on a substrate to become a membrane of thickness of 30~50 $\mu$ m under the temperature range of 80~100°C. Next, the membrane is sulfonated with the chlorosulfonic acid for one hour at room temperature under the circumstance of Nitrogen gas. After being taken out, the membrane is washed twice with ethyl acetate and then is gotten rid of residue acid by washing three times with deionized water and becomes an ionic membrane. Finally, the ionic membrane is dried for three hours in the temperature of 60~80°C to get a desired PVDF-g-SPS membrane.

Wherein, the thickness of the PVDF-g-SPS membrane is 40~70  $\mu$ m, and its outer appearance shows as pale coffee color, and its properties are as follows. (a) Under the analysis rate of 10°C/min shown in TGA, this membrane has excellent thermal stability at the temperature below 200°C, and is gradually decomposed at the temperature above 250°C, while 50% of entire structure is decomposed at temperature of 345°C.. (b) After being boiled in the boiling water for 30 minutes, the membrane is taken out from the water and wiped dry. Its water uptake is 20~30% by comparing the weights (water uptake =  $[(m_s - m_d)/m_d] \times 100\%$ , where  $m_s$  is the

mass of swelling membrane and  $m_d$  is the mass of dry membrane). (c) The conductivity of the membrane is 0.01S/cm by testing with the method of alternating impedance.

Next, the metalation is under proceeding: immerse this membrane in water solution of 1N sodium hydroxide for 10~14 hours to transfer its inside sulfonic acid group into sodium sulfonate group, then again immerse this membrane into the salt solution containing the Pt or Au cations for 18~26 hours to make the Pt or Au cations permeate into the membrane and proceed interchange reaction with the sodium ions, finally a reducing reaction is proceeded by the reducer of anion to get the desired electrode. Wherein, the described reducer may be sodium borohydride or sodium sulfite.

This membrane may be driven under the electric current of 1~3 Volt and 0.1~1.0 Hz and the vibration amplitude may reach 11.5mm in the electrolyte (electrode width is 3mm and electrode length is 30mm). Further, the vibration amplitude may reach 10mm and the application time may also reach 1500 hr after being packaged by silicone polymer.

### Second Embodiment

The manufacturing method for the PVDF-g-SPS according to this embodiment is similar to that of the first embodiment. The difference is that a Diak#1 (Hexamethylene diamine dicarboxylate) weighted 0.1~0.3 grams and a  $Pb_3O_4$  weighted 0.2~0.5 grams are added into the blend of PVDF-g-PS, poly ethyl acrylate, and PVDF resin. The membrane made by this solvent method is placed at temperature of 130°C~170°C for 1~3 hours to generate several cross-links in portion among the PVDF resin, PVDF-g-PS, and poly ethyl acrylate. The membrane according to this embodiment has following characteristics: thickness is 40~60 $\mu$ m, water uptake rate is 15~20%, while tensile strength may further reach the value of 300 kg/cm<sup>2</sup>.

Table 1 is an experimental result comparison between the embodiments according to the invention with commonly known methods. From Table 1, the membrane made simply by PVDF-g-SPS according to the prior art obviously cannot

be driven with low voltage; also it is too weak, easily broken and unable to swing. Further, the membrane made simply by PVDF-g-SPS/PVDF is also unable to be driven by low voltage and unable to swing, although the mechanical performance of the membrane is enhanced, but its flexibility is poor. Therefore, they all cannot be applied in EAPC.

However, the membrane composite made by the embodiments according to the invention (5 to 7) may be driven by low voltage and its thickness is thick enough to swing easily without breaking and its driving time is longer than that of Nafion.

Table 1

No.	Components (gram)	Hydrogen Containment ent (gram)	Equivalent W e i g h t (gram)	Membrane Thickness ( $\mu\text{m}$ )	Swing Test ( 5 V , 0.5Hz)	Notation
3	PVDF-g-SPS (2.75)	$1.0250 \times 10^{-2}$	--	110	Unable to swing	Easily broken, mechanical performance poor
4	PVDF (5.21)  PVDF-g-SPS (1.47)	$5.4963 \times 10^{-3}$	1215	75	Unable to swing	Hardness large, flexibility poor
5	PVDF (5.21)  PVDF-g-SPS (1.47)  Ethyl Acrylate (5.01)	$5.4963 \times 10^{-3}$	2127	140	Good	Swinging time is longer than that of Nafion 117
6	PVDF (9.38)  PVDF-g-SPS (2.21)  Ethyl Acrylate (7.52)	$8.2463 \times 10^{-3}$	2317	225	Good	Swinging time is longer than that of Nafion 117
7	PVDF (6.25)  PVDF-g-SPS (2.75)  Ethyl Acrylate (5.86)	$1.0250 \times 10^{-2}$	1449	220	Swinging amplitude is too large.	--

Note: the test piece is 3 cm long and 0.3 cm wide.

In summary, the fluoropolymer blend with high ionic conductivity provided by the present invention may be applied in the electroactive polymer composite (EAPC). The invention applies the PVDF-g-SPS as the fluoropolymer with high ionic conductivity, this polymer is produced by grafting the styrene onto PVDF followed by sulfonation, polymer blend is formed by mixing PVDF-g-SPS with the fluoro- or hydrocarbon-elastomer and PVDF resin has following merits:

(a) Excellent ionic conductivity ( $>0.01\text{S/cm}$ ) at room temperature.

(b) Excellent flexibility and stability; this membrane of compound material can be driven electrically and completely under the condition of 1V voltage and 0.5Hz frequency.

(c) If required by practice, this membrane of compound material may further be cross-linked appropriately with organic diamine or organic peroxide for enhancing its mechanical strength that may reach  $50\sim350\text{kg/cm}^2$ , while its water uptake rate may reach 5~50%.

(d) Stable thermal stability; this membrane of compound material is extremely stable at the temperature below  $200^\circ\text{C}$ , and is started to decompose gradually from the temperature above  $250^\circ\text{C}$ , while the decomposing temperature for 50% analyzed by the TGA is  $345^\circ\text{C}$ .

(e) Stable chemical stability; there is no decomposition phenomenon for storing this membrane of compound material in the solution of the range of PH 1~14 for the long term, while heated at the boiling water also for the long term, its flexibility is still maintained at good condition without destruction.

(f) Excellent replacement of salt; when this membrane of compound material is applied in the macromolecular composite driven by electricity or fuel cell and the noble metal is served as electrode material or catalyzer, since the salt replacement is good, so it is very important for manufacturing process.

(g) The obtained membrane not only has the merit of thick thickness of membrane and good function of driving performance, but also has characteristics



of excellent mechanical performance, compact structure, long swinging time, superior flexibility, and long maintenance of good conductivity, etc.

(h) The cost of this product is much cheaper than that of the known perfluorinated ionic polymer and it is easier to prepare.

While novel features of the present invention have been described with reference to one or more particular embodiments herein, those skilled in the art will recognize that many modifications and variations of the present invention are possible. Therefore, the scope of the present invention is to be limited only by the following claims.